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The Gulf of Mexico (GOM) is a semi-enclosed sea that connects in the east to the Atlantic ocean through the straits of Florida, and in the south to the Caribbean Sea through the Yucatan channel. The GOM is rich in natural resources and supports a large fisheries and oil and gas industry. The region is also impacted by natural events such as hurricanes necessitating a better understanding of the physical and biogeochemical processes in the region. Numerous field, remote sensing and numerical modeling studies have provided greater insights into various processes in the GOM, especially the Loop Current (LC) and its eddy field that is a dominating feature in the GOM. Numerical models such as the NRL Layered Ocean Model (NLOM) , the Navy Coastal Ocean Model (NCOM) (Barron et al. 2006), the Hybrid Coordinate Ocean Model (HYCOM) , the University of Colorado version of the Princeton Ocean Model (CUPOM) and remote sensing from altimeters have provided better insights into the LC, its eddies and its interaction with the waters of the GOM. Assimilation of SSH from satellite altimetry into these models have improved the accuracy of model predictions. In the GOM, an important consideration in assessing the performance of a numerical model is its accuracy in representing the observable features of the LC and its eddy field.

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# COMPARISON OF SEA SURFACE HEIGHTS DERIVED FROM THE NAVY COASTAL OCEAN MODEL WITH SATELLITE ALTIMETRY IN THE GULF OF MEXICO

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## 1. INTRODUCTION

The Gulf of Mexico (GOM) is a semi-enclosed sea that connects in the east to the Atlantic ocean through the straits of Florida, and in the south to the Caribbean Sea through the Yucatan channel. The GOM is rich in natural resources and supports a large fisheries and oil and gas industry. The region is also impacted by natural events such as hurricanes necessitating a better understanding of the physical and biogeochemical processes in the region. Numerous field, remote sensing and numerical modeling studies have provided greater insights into various processes in the GOM, especially the Loop Current (LC) and its eddy field that is a dominating feature in the GOM (Maul 1997; Vukovich and Maul 1985; Sturges and Leben 2000; Welsh and Inoue 2000; Oey et al. 2005). Numerical models such as the NRL Layered Ocean Model (NLOM) (Hurlburt and Thompson 1980), the Navy Coastal Ocean Model (NCOM) (Barron et al. 2006), the Hybrid Coordinate Ocean Model (HYCOM) (Chassignet et al. 2005), the University of Colorado version of the Princeton Ocean Model (CUPOM) (Kantha et al. 2005) and remote sensing from altimeters (Leben et al. 2002; Leben 2004) have provided better insights into the LC, its eddies and its interaction with the waters of the GOM. Assimilation of SSH from satellite altimetry into these models (Chassignet 2005) have improved the accuracy of model predictions. In the GOM, an important consideration in assessing the performance of a numerical model is its accuracy in representing the observable features of the LC and its eddy field (Oey et al. 2005).

One circulation model in operation for the Caribbean Sea, the Gulf of Mexico, the Straits of Florida, and parts of the western North Atlantic Ocean is the real-time ocean nowcast/forecast system that has been developed at the Naval Research Laboratory (Intra-Americas Sea Ocean Nowcast/Forecast System ( IASNFS). It is a 41-level, 1/24° (5-6 km) data assimilating ocean model based on the Navy Coastal Ocean Model (NCOM) (Martin, 2000; Ko et al. 2003; Ko et al. 2008). To generate the daily nowcast, a 72-hour hindcast is performed that is restarted from the previous days nowcast minus 48 hours. The reason for dropping back 48 hours before the previous days nowcast is to allow for data that has been late in arriving (Ko et al. 2003). During the nowcast, the ocean model continuously assimilates the three-dimensional ocean temperature/salinity analyses produced by a statistical data analysis model, the Modular Ocean Data Assimilation System (MODAS) (Carnes et al. 1998). Real-time satellite altimeter (GFO, Jason-1, ERS-2) sea surface height anomaly data as well as AVHRR sea surface temperature data are used by MODAS to generate the three-dimensional temperature and salinity analyses. The system is driven by the U.S Navy's global atmospheric model (NOGAPS) which consists of three-hourly nowcast/forecast of surface wind stress, sea level air pressure, solar radiation, and surface heat fluxes that are applied for surface forcing. The IASNFS produces a nowcast and a 72-hour forecast of sea level variation, 3-D ocean current, temperature, and salinity. The open boundary conditions (sea surface elevation, temperature, salinity and currents) are provided by the NRL 1/8° ( ~16.5 km) global NCOM

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model (Barron et al. 2006). The global NCOM model also provides a 3-5 day forecast of these boundary values each day. A one-way coupling with a nudging layer is used to ingest these boundary conditions into the IASNFS model. The discharge (monthly climatology) from 53 rivers is included as forcing in the IASNFS. The IASNFS has been shown to produce realistic ocean circulation for the major current systems in the Intra-Americas Sea.

Altimeter data are being used to map sea surface height (SSH), to monitor ocean circulation and biological linkages, modeling the distribution of heat in the ocean and assimilation into ocean circulation models (Wilson and Adamec 2001; Dong and Kelly 2004; Chassignet et al. 2005). The NASA/CNES Jason-1 satellite is a follow-on mission to the TOPEX/Poseidon mission that continues to provide high-accuracy SSH measurements. Jason-1 was launched on December 7, 2001 and the first cycle began on January 15, 2002. Altimeter data from Jason-1 and ERS-2 in conjunction with satellite sea-surface temperature are being assimilated into ocean circulation models such as NCOM for operational ocean monitoring and prediction. Here we examine the NCOM model results of sea surface height anomalies (SSHA) against Jason-1 satellite altimetry for the GOM.

## 2. METHODOLOGY

The study area comprises the whole Gulf of Mexico including the Yucatan Channel and part of the Florida Strait (Fig. 1). Fig. 1a shows the location of the NDBC buoys and the various passes of the Jason-1 satellite with the odd-numbered passes being the ascending and the even-numbered passes being descending. The SSHA data from Jason-1 were acquired from Physical Oceanography Distributed Active Archive Center (PO.DAAC) Jet Propulsion Laboratory and processed for the GOM region covering the period from 15$^{th}$ January 2002 to December 2006. The SSHA values represent the difference between the best estimate of the sea surface height and a mean sea surface. The sea surface height was corrected for atmospheric effects, effects due to surface conditions and other contributions such as ocean tides, pole tide, and inverse barometer. SSHA values are gridded to reference tracks which have standard latitude and longitude locations and are same for every cycle. A cycle contains up to 254 passes and represents a collection of data where the ground track of the Jason-1 satellite repeats itself approximately every 10 days. Data along all the tracks over the 10-day period were used to obtain SSHA maps of the GOM region using simple interpolation.

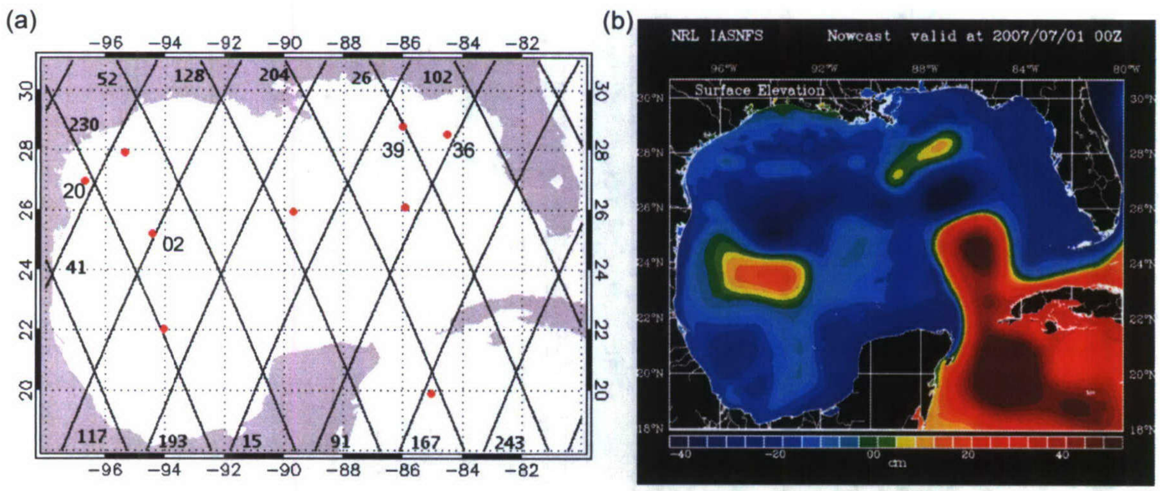


Fig. 1. (a) Map of the study area showing the ground-track lines of Jason-1. The red circles denote the locations of NDBC buoys located in the GOM. (b) Corresponding segment of the IASNFS NCOM model output of SSH used in the comparison study.

Model SSH forecasts for the period 2002 to 2006 were used in this study with 5-day averages of model results being used for comparisons with the Jason-1 altimeter data. Model SSH data were averaged over the entire period and subtracted from the 5-day average SSH fields to derive model SSHA or variations. Along-track Jason-1 SSHA obtained each 10-day window were compared to the closest 5-day model SSHA along the satellite tracks. Comparisons were also made at a few NDBC buoy locations (nearshore and offshore) as part of a related study to examine other model outputs such as sea surface temperature and salinity. Images of SSHA maps were also obtained from the Colorado Center for Astrodynamics Research (CCAR) at the University of Colorado, Boulder from an Internet site maintained by Robert Leben (Leben et al. 2002).

## 3. RESULTS/DISCUSSION

The Loop Current in the GOM is part of the Gulf Stream system and can be observed as the region with high SSH in the eastern part of the GOM and in the Yucatan Peninsula (Fig. 1b). The Loop Current sheds anticylonic eddies or warm-core rings at irregular intervals (Vukovich 1988). The separated warm core rings (sea surface highs) propagate westward and greatly influences circulation in the GOM (Fig. 1b). Cyclonic features or cold core eddies (sea surface lows) often break these anti-cyclonic rings into smaller eddies (Biggs et al. 1996). Cyclonic eddies in the Gulf are however smaller (typically 50-100 km in diameter) than the anticyclonic eddies and have shorter life times. The dynamics of these eddies (both cyclonic and anti-cyclonic) have been revealed in greater detail through the use of multi-satellite altimetry data (Leben 2002; Leben 2004).

Jason-1 SSHA map (Fig. 2a) during cycle 1 (15-24 January, 2002) indicates an elongated warm core ring in the middle of the Gulf. NCOM model SSHA during the same period however shows a smaller size warm core ring (Fig. 2b). For comparison, SSHA map obtained from CCAR which used multi-satellite altimetry data (Fig. 2d) also confirmed the presence of an elongated warm core eddy that appears similar to Fig. 2a. Three smaller size cold core rings observed in the model output (Fig. 2b) are also observed in the multi-satellite altimetry map (Fig. 2d) but are however not clearly defined in the Jason-1 anomaly map (Fig. 1a). It is possible that these cold core rings could go undetected due to their small size as they could fall in between the repeat tracks of the Jason-1 satellite (Fig. 2c). These features also appear to be smeared in the Jason-1 SSHA 10-day composite map due to the large spacing (~200 km) between the Jason-1 tracks in the Gulf. The use of multi-satellite altimetry data appears to provide a better detection of these smaller features although some smearing is visible in comparison to the clear outline of the three cold core rings in the model output. Satellite along-track differences between model output and Jason-1 indicate regions in the Gulf where model output matches or deviates from the Jason-1 SSHA estimates. Largest differences appear to occur at or near the warm core ring in the middle of the Gulf where the model overestimated SSH. The elongated nature of the core ring observed in satellite altimetry suggests that the model underestimated the SSH to the east of the Gulf. Smaller differences were observed in the LC, along the Yucatan Channel and the Bay of Campeche suggesting better agreement between model and altimetry data at these locations.

A similar comparison between the Jason-1 and model SSHA maps for cycle 182 (21-30 December, 2006) suggest very similar patterns of SSHA distributions, however model results indicate greater intensity of warm core and cold core rings (Fig. 3a, b). Also we observe greater positive model anomalies along the Gulf and west Florida coast. Two warm core rings in the center of the Gulf appear to be separated by a cold core ring that could have previously cleaved the warm core ring into two smaller warm core rings. The SSHA map obtained from CCAR also shows patterns of SSH anomalies similar to those of the model. However the anomaly intensities were smaller in comparison to the model prediction. Largest differences between the model and Jason-1 SSHA along the satellite tracks (Fig. 3c) were

observed at the locations of the warm and cold core rings suggesting overestimates of model outputs at these locations.

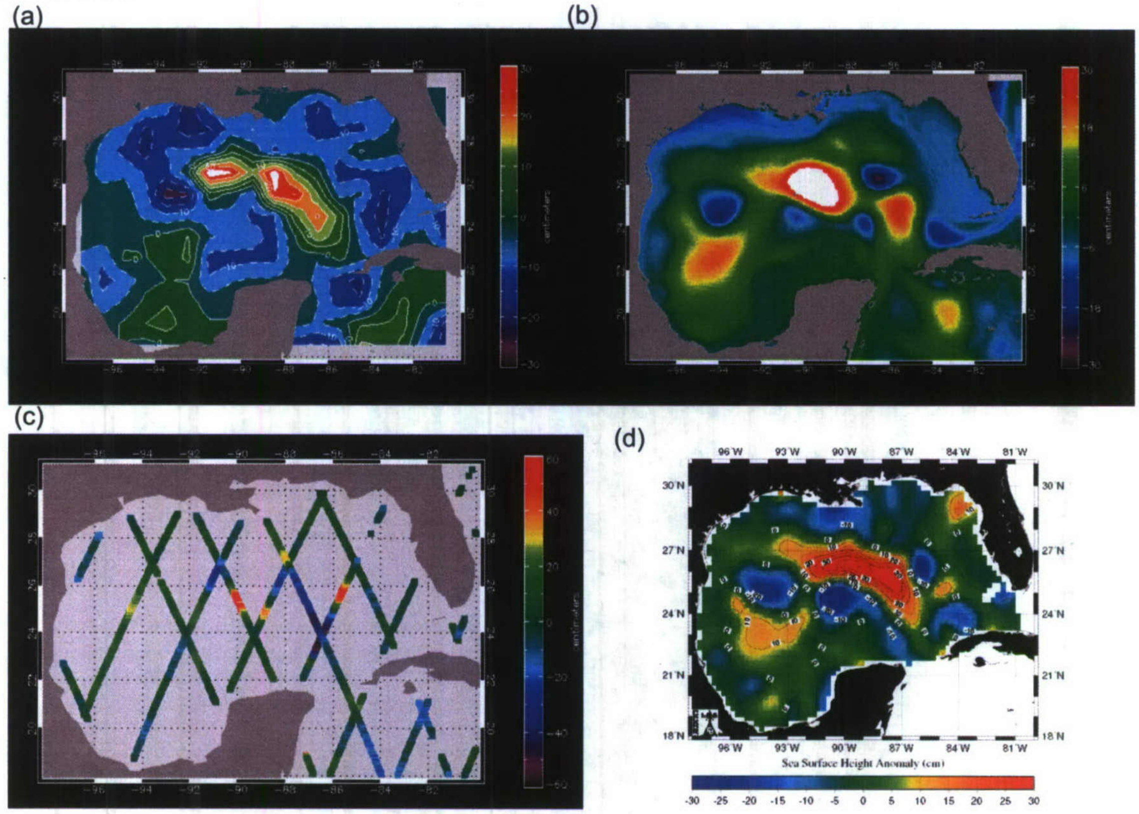


Fig. 2. (a) Jason-1 SSHA map of the Gulf of Mexico obtained by interpolation of along-track SSHA during cycle 1 (15-24 January, 2002). (b) SSHA derived from NCOM model for the period corresponding to the Jason cycle 1. (c) Jason-1 along-track differences (cm) of SSHA between NCOM model and Jason. (d) SSHA map obtained from CCAR using multi-satellite altimetry observations during the same period.

With Jason-1 SSHA data having been shown to be quite accurate (~ 3 cm accuracy), time-series analysis of root-mean-squared (RMS) differences between Jason-1 and model outputs along each of the satellite tracks in the Gulf of Mexico (e.g., Fig. 1a, 2c) should provide information on the spatial and temporal differences between model and altimetry derived SSHA. An examination of RMS differences for all cycles in 2002 for the different tracks in the Gulf suggest both temporal and spatial differences in SSHA, with the lowest differences observed along nearshore track 41 in the western GOM (Fig. 4). Although tracks 117 and 193 in the western Gulf also showed the low differences between model and Jason-1 SSHA, larger RMS differences observed during the first few cycles in 2002 may have been associated with the warm core ring that was present in the western Gulf (Fig. 2b) and the higher level of model SSHA in comparison to Jason-1 in the region of the warm core ring. The largest RMS difference was measured along track 91 which transects the western part of the Gulf between the Yucatan peninsula and the Florida Panhandle. This track transects the most active region of the Gulf with highest variability in SSHA associated with LC instability and eddy separation (Vukovich et al. 1979; Vukovich and Maul 1985). Track 102 transects mainly through a short distance across the Florida Strait and also reveals large variability associated with the flow of LC through the Florida Strait. RMS differences during the years 2003, 2004, 2005 and 2006 also revealed similar range in the variability but temporal patterns associated with different tracks varied (not shown).

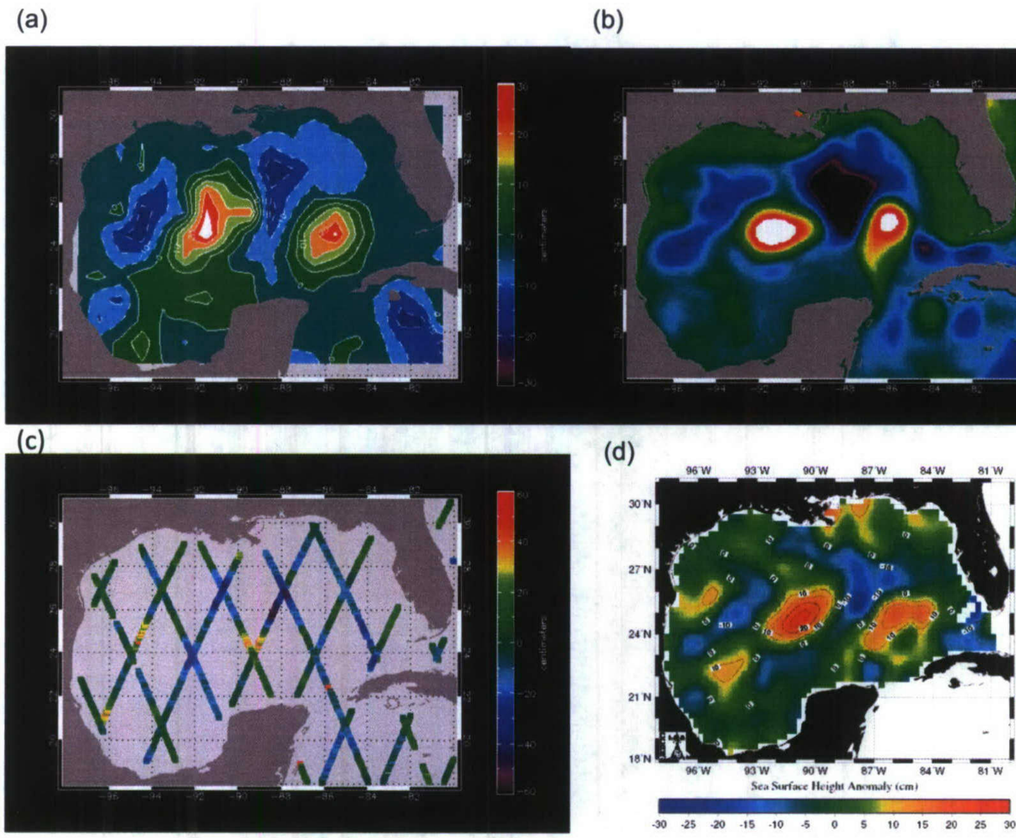


Fig. 3. a) Jason-1 SSHA (cm) map of the Gulf of Mexico obtained by interpolation of along-track SSHA during cycle 182 (21-30 December 2006). (b) SSHA derived from NCOM model for the period corresponding to the Jason cycle 182. (c) Jason-1 along-track differences of SSHA between Jason and the NCOM model. (d) SSHA map obtained from CCAR using multi-satellite altimetry observations during the same period.

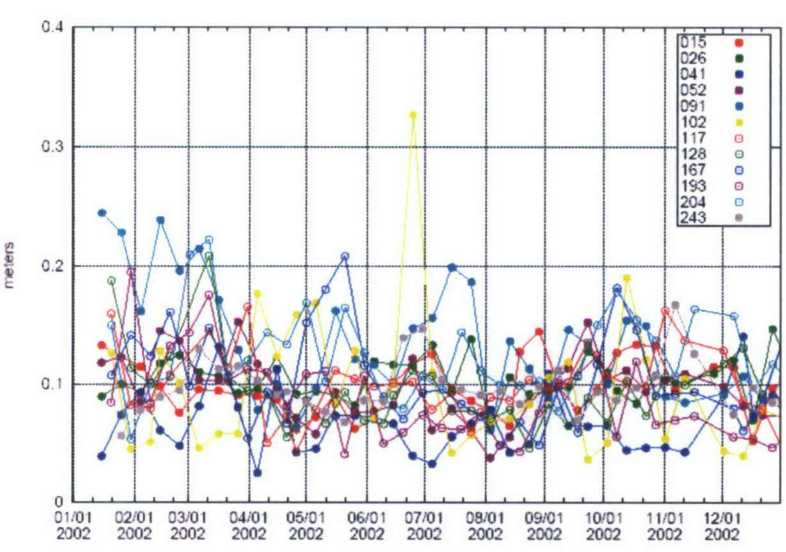


Fig. 4. SSHA root-mean-square (RMS) difference between NCOM model output and Jason-1 tracks in the Gulf of Mexico for the year 2002.

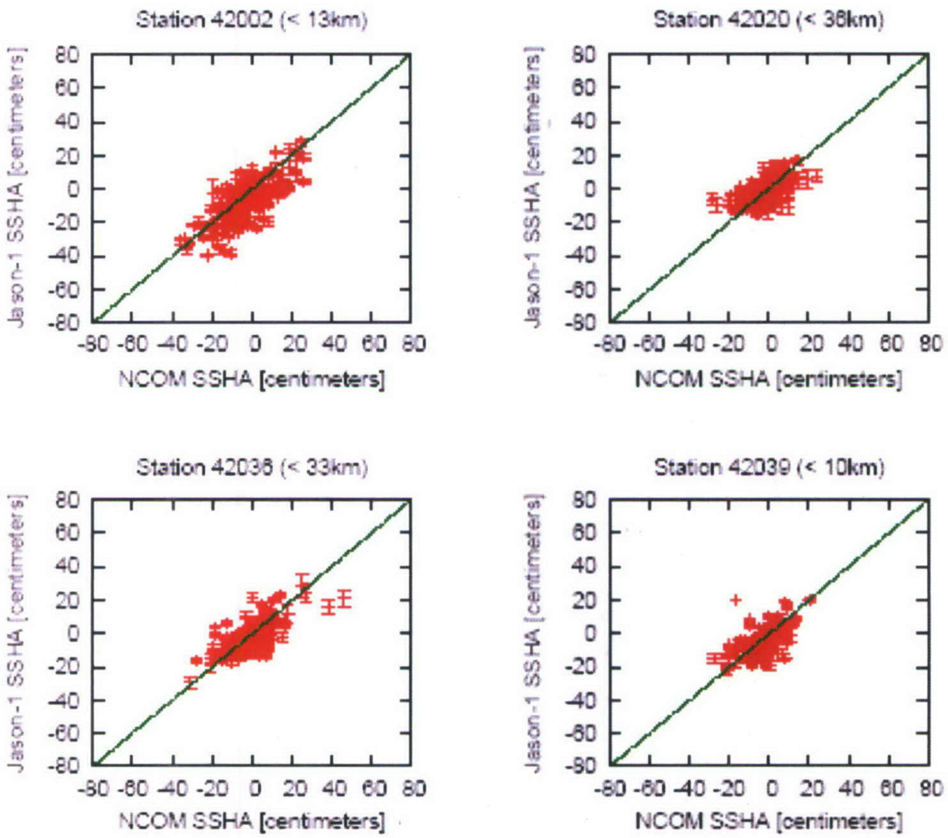


Fig. 5. Correlation between Jason-1 and NCOM model SSH anomalies in the Gulf of Mexico at one offshore (42002) and three nearshore buoys (42020, 42036, and 42039) NDBC buoy locations.

In Figure 5 we further examine correlations between Jason-1 and model SSH anomalies at four NDBC buoy locations (one offshore and three nearshore) closest to the satellite pass. Overall model and altimetry SSHA appear to be well correlated, with nearshore stations showing smaller range in SSHA variability (± 20 cm) than the offshore station (± 40 cm).

## 4. CONCLUSION

In this paper we have assessed the performance of the 1/24° NCOM model derived SSHA fields for the Gulf of Mexico against Jason-1 altimetry derived data for the period 2002 to 2006. It appears that the salient features of warm and cold core rings observed in satellite altimetry are well represented by the NCOM model. While the larger warm core rings are observed in both the model and interpolated Jason-1 data, smaller cyclonic cold core rings appear smeared in the interpolated Jason-1 altimetry maps. However, multi-satellite altimetry improves the representation of these features. Time series analysis of along-track Jason-1 and model SSHA data suggest smaller differences along the western Gulf where eddy activity is much reduced. Largest differences between model and satellite SSHA are observed in the middle and eastern Gulf where LC variability and eddy activity are significant. Overall, SSHA were greater in model forecast than satellite derived observations. These suggest implications in model derived heat budgets for the region.

## 5. ACKNOWLEDGMENTS

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